# Tripwire system for fixed line array processing

Mr. Sunil Mathews, Dr. Mary H. Johnson, Dr. Robert Latourette, Mr. Sami Deeb and Ms. Beth Kocab
Naval Undersea Warfare Center Code 1522
1176 Howell Street, Newport, RI 02841 USA

***Abstract-***

**We have devised a system to automatically detect, manage and track contacts with a stationary line array. The array has a large number of elements, and the ability to process any subset of these elements (up to a fixed number) at any given time. Detection is accomplished by fixed detection apertures spaced along the array such that the apertures create a "tripwire" range parallel to the length of the array. Contacts crossing the tripwire range are handed off to an automated tracking aperture which adjusts its aperture size and aperture center along the array to track the contact using the best subset of elements. The adaptive detection scheme conserves limited tracker resources by limiting the trackers to those contacts which appear to be heading towards the line array. This system has been0 implemented on a Mercury Adapdev system and has been tested using simulation of multiple approaching contacts with interfering distant contacts.**

## I. INTRODUCTION

We have devised a system to automatically detect, manage and track contacts with a stationary line array. The array has a large number of elements, and the ability to process any subset of these elements (up to a fixed number) at any given time.

The detection scheme is designed to conserve limited tracker resources by limiting the trackers to contacts that appear to be heading towards the line array. Detection is accomplished by automated broadband energy followers operating on fixed detection apertures spaced along the array such that the apertures create a "tripwire" range parallel to the length of the array. A detection management system was built to handle the detection aperture contacts. Contact followers (CF) are automatically assigned to all detections in these apertures. The detection system can track numerous contacts in bearing and range in both near field and far field in each detection aperture.

Contacts that cross into the tripwire range and are closing are handed off to a tracking aperture, which adjusts its location along the array to track the contact using the best subset of elements. Candidate CF's are used as detections to automatically assign the range-focused trackers. The tracker aperture is then allowed to "rove" along the length of the array to keep up with contact dynamics. The tracker also adjusts its aperture size with the changing range of the contact. The tracker incorporates its own range-focused beamformer utilizing a three beam interpolation in azimuth and inverse-range space. It uses an adaptive gain alpha-beta filter for state estimates. The predicted state estimates provide range and bearing estimates to reset the tracker beamformer aperture to the new position. There are a limited number of these trackers since they require front-end beamformer functionality and run at a faster rate to handle contact dynamics. The track management function oversees the tracker, and adds and drops them based on multiple criteria such as contact opening or closing and signal to noise information.

This system is implemented on a Mercury Adapdev system and has been tested using simulation of multiple approaching contacts with interfering distant contacts.

This paper focuses on the tripwire detection and localization scheme. In Section II, the range focused tripwire concept is developed in detail. Section III discusses the application of the tripwire to the long line array detection system. Section IV shows simulation results.

## II. RANGE FOCUSED TRIPWIRE PROCESSING

### *A. Range Focused Beamforming*

A key concept in the definition of this detection scheme is design of the focus range sets for a long line array, specifically line arrays of sufficient length such that the near field extends out past ranges of practical importance

$$\frac{L^2 \cdot f}{C} > R_{significan\ t}$$

Where L is the aperture length; f is frequency and C is the speed of sound in water as defined in [1].

In order to provide full coverage of ranges of practical importance that would be degraded by a plane wave (infinite range) beam set, one or more beam sets focused at closer finite ranges will be required. Define a focus range set $R_j(\theta)$ as specifying a set of ranges as a function of bearing θ referenced to the center of a line array. Let j = {0, 1, 2, …, N} be integers representing nested consecutive focus range sets such that

$$R_0(\theta) \geq R_1(\theta) \geq R_2(\theta) \geq .... \geq R_j(\theta)\ \forall \theta : 0^\circ \leq \theta \leq 180^\circ$$

The focus range set $R_j(\theta)$ , j= {0, 1, 2, … N} represent range and bearing coverage with respect to a line array. The farthest range as a function of bearing coverage is specified by $R_0(\theta)$ and the closest range as a function of bearing coverage is specified by $R_N(\theta)$.

We begin our study of focus range design by examining the time delay equation between a point in space (bearing θ and range R) and an array element. This analysis will yield insight into focus range design. [2], [3], and [4] contain additional treatments of range focusing.

We will assume a long line array centered on the x-axis. The point in space which we wish to beamform to is assumed to be at a range R from the center of the line array and at an angle θ from the center of the line array. Let $d_i$ be the $i^{th}$ sensor

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14. ABSTRACT

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location on the line array. Fig. 1 illustrates this geometry. Using the law of cosines we can write the following equation representing the coherent contact signal's time of arrival difference $\tau_i$ between sensor $d_i$ and the center of the line array, given speed of sound C.

$$\tau_i(\theta, R) = \frac{R - \sqrt{R^2 - 2 \cdot R \cdot d_i \cdot \cos\theta + d_i^2}}{C} \quad (1)$$

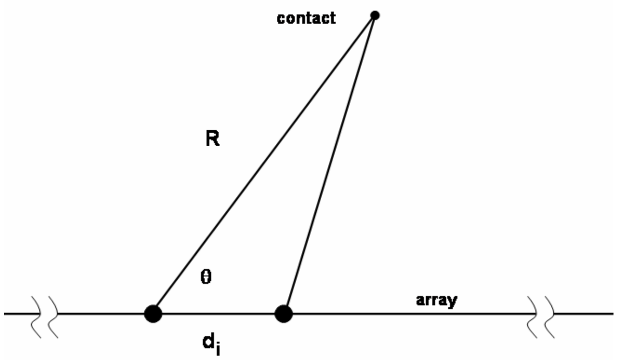


**Figure 1: Near field geometry**

The following trick results in a very accurate approximation and yields insight into focused beamforming. For the purposes of this study, and in order to support the two approximations to follow, we shall assume that $R \gg d_i \cdot \cos\theta$, that is, the range is much larger than the array element spacing.

A little algebra, completing the square, and using of the identity $\sin^2\theta + \cos^2\theta = 1$ yields the following

$$\tau_i(\theta, R) = \frac{R - \sqrt{(R - d_i \cdot \cos\theta)^2 + d_i^2 \cdot \sin^2\theta}}{C} \quad (2)$$

Factoring out the dominant term yields

$$\tau_i(\theta, R) = \frac{R - (R - d_i \cdot \cos\theta) \cdot \sqrt{1 + \frac{d_i^2 \cdot \sin^2\theta}{(R - d_i \cdot \cos\theta)^2}}}{C} \quad (3)$$

Now we apply the following approximation to (3)

$$\sqrt{1 + a} \approx 1 + \frac{a}{2} \ \textit{for}\ a \ll 1 \quad (4)$$

Which yields

$$\tau_i(\theta, R) \approx \frac{R - (R - d_i \cdot \cos\theta) \cdot \left(1 + \frac{d_i^2 \cdot \sin^2\theta}{2 \cdot (R - d_i \cdot \cos\theta)^2}\right)}{C} \quad (5)$$

and finally after some algebra

$$\tau_i(\theta, R) \approx \frac{d_i \cdot \cos\theta}{C} - \frac{d_i^2 \cdot \sin^2\theta}{2 \cdot (R - d_i \cdot \cos\theta) \cdot C} \quad (6)$$

Equation (6) can be approximated as

$$\tau_i(\theta, R) \approx \frac{d_i \cdot \cos\theta}{C} - \frac{d_i^2 \cdot \sin^2\theta}{2 \cdot R \cdot C} \quad (7)$$

The first term is the standard delay for plane wave beamforming of a far field contact at angle θ to the center of the line array. The second term is the time delay correction for a near field contact at range R from the line array. The second term is of primary interest. This term is effectively added to a plane wave beamformer to produce a focus beam at range R and bearing θ.

We will now look at the time delay difference between a beam in focus range j focused to range $R_j(\theta)$ and bearing θ and a focus range j+1 focused to range $R_{j+1}(\theta)$ and bearing θ.

$$\tau_i(\theta, R_{j+1}) - \tau(\theta, R_j) = \frac{d_i^2}{2 \cdot C} \cdot \sin^2\theta \cdot \left(\frac{1}{R_j(\theta)} - \frac{1}{R_{j+1}(\theta)}\right) \quad (8)$$

Now if we require the scalloping loss, i.e., the maximum reduction in power between any pair of beams focused on the same bearing in adjacent focus range sets, to be constant for all bearings $\theta$ and all focus range sets $j$, then we require

$$\sin^2\theta \cdot \left(\frac{1}{R_j(\theta)} - \frac{1}{R_{j+1}(\theta)}\right) = Const, \quad \forall\theta\,\forall j \quad (9)$$

Let us define a constant parameter $\Delta$ as shown below:

$$\Delta = \frac{1}{R_{j+1}(90^\circ)} - \frac{1}{R_j(90^\circ)} \quad (10)$$

The parameter $\Delta$ specifies the desired spacing between focus range sets at $90^0$ to be a constant $\Delta$ and thus effectively specifies the desired range scalloping loss between adjacent focus ranges sets.

We can now define the relationship between the focus ranges of each pair of beams in adjacent focus range sets as shown below, resulting in a fixed range scalloping loss with respect to focus range set $R_{j+1}(\theta)$ for all common bearing angles θ.

$$\frac{1}{R_{j+1}(\theta)} - \frac{1}{R_j(\theta)} = \frac{\Delta}{\sin^2(\theta)} \ \textit{for}\ 0^\circ \le \theta \le 180^\circ \quad (11)$$

## B. *One Degree of Freedom*

Given a particular focus range set $R_j(\theta)$, the following relationship with the other focus range sets will guarantee a fixed range scalloping loss at common bearing angle θ between all adjacent focus range sets at all bearing angles.

$$\cdots\frac{1}{R_{j+1}(\theta)}-\frac{1}{R_j(\theta)}=\frac{1}{R_j(\theta)}-\frac{1}{R_{j-1}(\theta)}\cdots=\frac{\Delta}{\sin^2(\theta)} \qquad (12)$$
$$for\ 0^\circ \le \theta \le 180^\circ$$

There is no implied restriction on the definition of focus range set $R_j(\theta)$, except $R_j(\theta)$ can not equal 0. We will allow focus ranges to become large negative ranges (beyond infinite range) for now. Looking at (12) it becomes apparent that we can arbitrarily define the range versus bearing of one focus range set and then under the assumption of equal scalloping loss everywhere the other focus range sets will be determined. Thus we claim that the definitions of focus range sets with the property of maintaining the same fixed scalloping loss between adjacent focus range sets at common bearing angles has one degree of freedom, i.e., the definition of one of the focus range sets. In theory there are an infinite number of possible definitions of focus range sets. We shall concern ourselves with the important class of focus range set definition where we maintain a constant power response at a given range $R_{fix}$ for all bearing angles θ. (Note that $R_{fix}$ does not have to be a member of any of the defined focus range sets $R_j$.) The natural algorithm of forming a plane wave beamformer at infinite range followed by a number of closer finite focus ranges is a subset of this class.

### C. *Constant Power Response at a Fixed Range Across Bearing*

We shall now derive expressions that define focus range sets that contain a constant power response at a fixed range for all bearings.

With (10) in mind the following equation satisfies (11) for all focus range sets represented by the integers j=0, 1, 2, …N where $R_0(\theta)$ is the farthest focus range set.

$$\frac{\dfrac{1}{R_{j+i}(\theta)}-\dfrac{1}{R_i(\theta)}}{\dfrac{\Delta}{\sin^2(\theta)}}=j \qquad (13)$$

Let i=0 and thus $R_0(\theta)$ is the farthest focus range set. Equation (13) can be rewritten as follows.

$$\frac{\dfrac{1}{R_j(\theta)}-\dfrac{1}{R_0(\theta)}}{\dfrac{\Delta}{\sin^2(\theta)}}=j \qquad (14)$$

Note that $j$ is effectively a linear function of focus range set index. Integer values of $j$ correspond to focus range sets we have designed to have a fixed scalloping loss between adjacent sets for all bearings. $j$ has the range of $0 \ge j \ge N$ where $j=0$ is the farthest focus range set and $j=N$ is the nearest focus range set.

For convenience we will define the range $R_{fix}$ where we want to have a constant power response in terms of the parameter Δ and a selectable parameter b.

$$\frac{1}{R_{fix}}=b\cdot\Delta \qquad (15)$$

We will now define where we want to place $R_{fix}$ with respect to our focus range sets j=0, 1, 2, …, N We will place $R_{fix}$ at a range set index of "a" Therefore $R_a(\theta)=R_{fix}$ and using (14) we can write the following equation.

$$\frac{\dfrac{1}{R_{fix}}-\dfrac{1}{R_0(\theta)}}{\dfrac{\Delta}{\sin^2(\theta)}}=a \qquad (16)$$

If we now solve (16) for $\dfrac{1}{R_0(\theta)}$ we have the following

$$\frac{1}{R_0(\theta)}=\frac{1}{R_{fix}}-a\cdot\frac{\Delta}{\sin^2(\theta)} \qquad (17)$$

Substituting (17) and (15) into (14) we have

$$\frac{\dfrac{1}{R_j(\theta)}-b\cdot\Delta+a\cdot\dfrac{\Delta}{\sin^2(\theta)}}{\dfrac{\Delta}{\sin^2(\theta)}}=j \qquad (18)$$

Solving for $R_j(\theta)$ we have

$$R_j(\theta)=\frac{\sin^2(\theta)}{\Delta}\cdot\frac{1}{j-a+b\cdot\sin^2(\theta)} \quad j=0,1,2...,N \qquad (19)$$

### D. *Observations*

For j > a, the focus ranges $R_j(\theta)$ will decrease as θ moves away from $90^0$. For focus range indices j < a the focus ranges $R_j(\theta)$ will increase as θ moves away from $90^0$. In fact they will achieve infinite range (plane wave) when $\sin^2(\theta)=\frac{a-j}{b}$. As θ continues to move further away from $90^0$ the ranges will become finite and negative. There is nothing wrong with this mathematically or in practice. The negative ranges will be in focus at no realizable positive range, but will maintain the correct relationship with the other focus range sets. In practice a designer may wish to limit negative focus ranges to infinite range and abandon the design relationship with the adjacent closer focus range set.

### *E. Practical Designs*

For many practical designs the choice of $R_{fix}$ would be one of the natural focus range sets (we would want one of our focus range sets to at a constant range as a function of bearing.) In this case the parameter "a" would be one of the integers between 0 and N. A more interesting, and in our case, more useful choice is to make the scalloping range between two focus range sets be at a constant range as a function of bearing. This implies that contacts more focused in more distant focus range sets would be at a range greater then $R_{fix}$ independent of bearing and contacts more focused in closer focus range sets would be at a range less then $R_{fix}$ independent of bearing and contacts. For this case the parameter $a$ could take on the values {-1/2, 1/2, 1+1/2, 2+1/2, …, N+1/2}.

For many reasons it may not be desirable to set the farthest focus range to infinite range at $90^0$ ($R_0(90^0)$). A reasonable alternative is to set the range corresponding to a bearing of $90^0$ to have a power loss at infinite range equal to the scalloping loss. Set j=0, $\theta=90^0$ and $R_0(90^0)=2/\Delta$ in (19) to obtain the correct relationship between the parameters $a$ and $b$ for this case.

$$b-a=\frac{1}{2} \tag{20}$$

Under this condition the relationship between the parameter $a$ and the range $R_{fix}$ of constant power can be obtained by substituting (20) into (19) and letting $j=a$.

$$R_{fix}=\frac{1}{\Delta\cdot(a+.5)} \tag{21}$$

Finally the standard definition of focus range sets with the farthest focus range set being set at infinite range for all bearings (plane wave beamformer) can be obtained from (19) by setting $a=0$ and $b=0$ resulting in

$$R_j(\theta)=\frac{\sin^2(\theta)}{\Delta\cdot j},\quad j=0,1,2...,N \tag{22}$$

Note j=0 corresponds to infinite range i.e. a plane wave beamformer.

### *F. Summary*

1) Selecting the parameter Δ specifies the desired scalloping loss between adjacent focus ranges.
2) Maintaining the following relationship between adjacent focus ranges guarantees a constant scalloping loss at all bearings

$$\frac{1}{R_{j+1}(\theta)}-\frac{1}{R_j(\theta)}=\frac{\Delta}{\sin^2(\theta)}\ \ for\ 0^\circ\le\theta\le180^\circ$$

3) Defining focus ranges for each focus range set by the following equation guarantees a constant scalloping loss at all bearings between adjacent focus range sets but also specifies a given focus range where the power response is constant for all bearings.

$$R_j(\theta)=\frac{\sin^2(\theta)}{\Delta}\cdot\frac{1}{j-a+b\cdot\sin^2(\theta)}\quad j=0,1,2...,N$$

4) Careful selection of the parameters "a" and "b" allow customizing the focus range sets to meet particular design goals.

## III. Application to Long Line Array Tripwire Detection

The range focused tripwire concept was applied to the problem of automated detection on a long line array with a large number of elements. In this case, the detection system is required to sort out contacts and pass on to the track management system only those meeting the profile of being in close proximity and closing on the array. As a result, two range focus beam sets were chosen, near-field and far-field, based on the choice of a tripwire range set defining the proximity at which the contact should be assigned to a tracker.

Given the desired tripwire range, $R_{fix}$, we select $a=1/2$ to set the constant range tripwire between range 0 and range 1. As discussed above, these conditions determine the focus ranges for $R_0(\theta)$ and $R_1(\theta)$, sketched in Fig. 2.

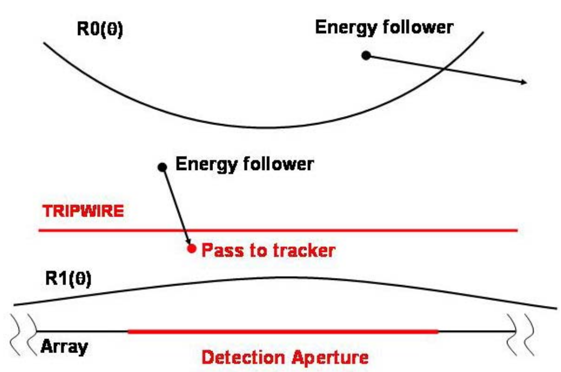


**Figure 2: Tripwire detection scheme**

In our application the ranges appear as in Fig. 3. Note that the decision to use fixed far field ranges instead of the negative ranges discussed in Section II result in curved regions of the tripwire range near endfire. Practically speaking, ranging performance is best for those beams focused on angles within approximately 30 degrees of broadside. Thus, a single detection aperture provides excellent coverage of the tripwire range within a 60 degree wide azimuthal swath as shown in Fig. 4.

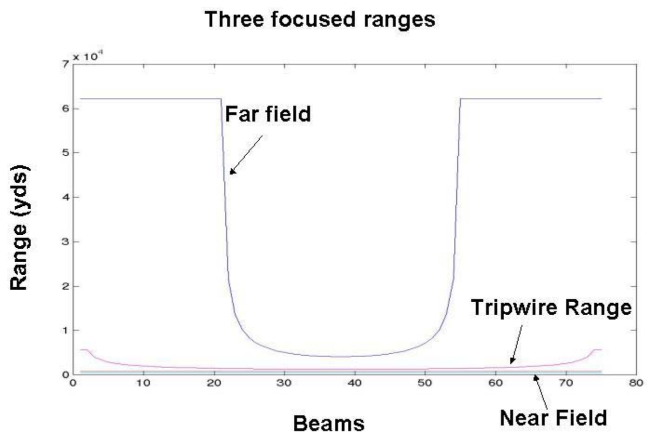


**Figure 3: Tripwire range sets for long line array**

The length of the array allows for multiple detection apertures to be processed. The detection apertures are spaced along the array as shown in Fig. 5 and the detection manager limits the extent of the beams in each detection aperture fan to support identifying the closest aperture as a contact passes inside the tripwire range, so that there is sufficient scalloping loss between the outer beams of adjacent apertures at the tripwire range.

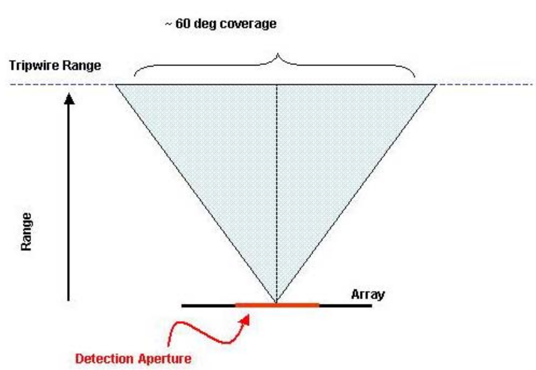


**Figure 4: Single Detection Aperture**

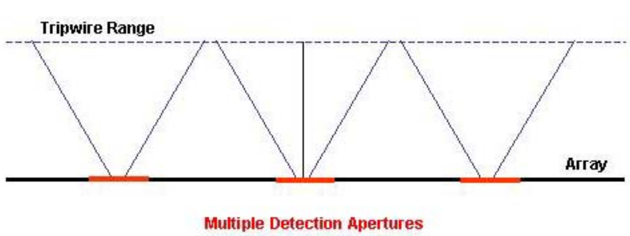


**Figure 5: Multiple Apertures Create Tripwire along the Length of the Array**

## IV. Simulation Results

Two time cuts of beamformed data for an example scenario in a single aperture are shown in Fig. 6. (Note that the additional, inner, range window shown was added for use in the tracker manager, not discussed in this paper.) Four contacts were simulated; two were stationary (labeled 1 and 4 in Fig. 6) and outside the tripwire range, while the two dynamic contacts started at 070 and 090 degrees respectively, relative to the aperture center and crossed over the line array. These contacts are labeled 2 and 3.

The first time cut labeled "Approaching CPA" shows an early cut of the data. All four contacts are initially and correctly focused in the R0 (far) window, representing the furthest focus range. Looking at the R1 (mid) window, notice that the two outside contacts, which are furthest from the array, are more defocused than the closer, dynamic, contacts which become more focused over time as they move closer to the array. The defocusing is most pronounced in the innermost R2 (near) window.

The second time cut labeled "CPA" shows data from the same contacts around the time when the two dynamic contacts pass CPA (closest point of approach) directly over the array simultaneously. Both dynamic contacts are focused in the R1 (mid) window for most of this time period, while the static contacts remain focused in the R0 (far) window. The first contact passes over at the left edge of the aperture, moving rapidly through the beams as it approaches and departs. The second contact passes directly over the center of the detection aperture, focusing in the R2 (near) window at the time closest to CPA and defocusing everywhere as it reaches CPA (partially a result of the fixed detection aperture.)

## V. Summary

We described the detection processing scheme used for a stationary long line array designed to automatically detect, manage and track contacts. A set of range focused beamsets were designed to provide a constant range tripwire for automated identification of contacts approaching the line array and were replicated over multiple apertures along the length of the array. A simulation example was presented to illustrate the localization concepts of this approach.

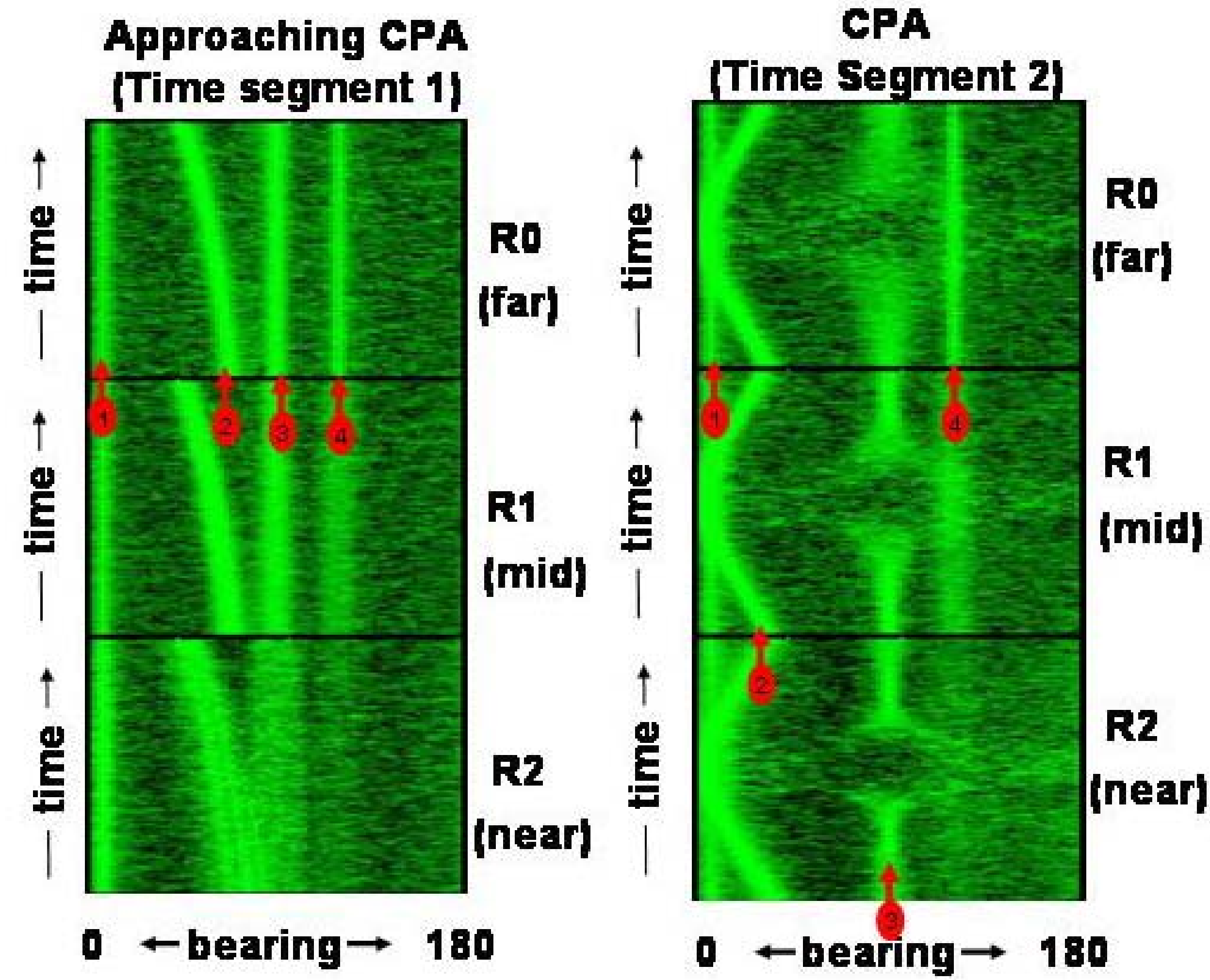


**Figure 6: Simulation Example showing multiple range windows for a single detection aperture. Contacts 1 and 4 are stationary far field contacts. Contacts 2 and 3 are approaching the array. Contact 2 crosses the array at CPA to the left of the detection aperture in the R1 window. Contact 3 crosses the array at CPA in the center of the detection aperture in the R2 window.**


## ACKNOWLEDGMENTS

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